I. REVIEW OF STATE-OF-THE-ART

Activity in the optical maser area has grown very rapidly in the last two years. The first paper clearly outlining the manner in which maser action could be attained and utilized appeared only three years ago.[1] One indication of the interest in optical masers is that over 400 organizations in the United States have bought rubies to make optical masers from the main U.S. supplier. As background for this report, the committee investigated the programs of about 40 organizations that appeared to be doing the most significant work.

At the present time, the operation of fourteen different infrared or optical masers has been announced. All but the organic system were first operated in the U.S. A brief table summarizing their characteristics is given below.

Infrared and Optical Masers in Order of Date of Successful Operation

.05% Cr^{+++} in Al_2O_3 crystal	6943A.	pulsed
.5% Cr^{+++} in Al_2O_3 crystal	7009A., 7041A.	pulsed
Sm^{++} in CaF_2 crystal	7082A.	pulsed
U^{+++} in CaF_2 crystal	22000-26000A.	pulsed
U^{+++} in BaF_2 crystal	24000A., 27000A.	pulsed
Ne in He gas discharge	11,180A.,	continuous
	11,530A.,	continuous
	11,600A.,	continuous
	11,990A.,	continuous
	12,070A.	continuous
Nd^{+++} in $CaWO_4$ crystal	10,600A.	continuous
Nd^{+++} in glass	10,600A.	pulsed
Pr^{+++} in $CaWO_4$ crystal	10,470A.	pulsed
Nd^{+++} in $SrMoO_4$ crystal	10,600A.	pulsed
Nd^{+++} in CaF_2	10,600A.	pulsed
Benzophenone and naphthalene in glass	4,700A.	pulsed

[1] A. L. Schawlow and C. H. Townes, Physical Review 112, 1940 (Dec. 15, 1958)

Tm^{+++} in $CaWO_4$	19,110A.	pulsed
Ho^{+++} in $CaWO_4$	20,460A.	pulsed

The pink ruby (.05% CR^{+++} in Al_2O_3) laser is the most thoroughly investigated and developed. It is a three-level laser in which light is absorbed by bands in the green and violet and emitted in the red at about 6940A, in a transition that ends on the ground state. Since more than one-half of the atoms must be raised to the upper of the two levels of the maser transition, there is a relatively high pumping energy required in order to reach the threshold of oscillation. Continuous operation in ruby has not yet been attained, primarily because of the difficulty of supplying enough pumping power without excessively heating the crystal and pumping light source. The output wavelength of the laser can be tuned over approximately twenty angstroms by varying the temperature of the ruby. Ruby lasers are usually pumped with light from xenon discharge tubes.

The following ruby operating characteristics have been obtained -- not all in the same experiment.

peak power	15 megawatts
maximum energy per pulse	50 joules
pulse duration	3×10^{-8} sec. to 2×10^{-3} sec.
minimum beam divergence	1/2000 radian
minimum pump input energy	70 joules
maximum ruby size	8" long, 3/4" diameter

Current development is stressing improvements in all of these characteristics. Rubies of greater size and of better optical quality are being developed, which should increase the energy per pulse and allow for a decrease in the divergence angle and pump energy required to reach threshold for oscillation.

Several techniques have been demonstrated or are under development to increase peak power and decrease the pulse length of ruby lasers. A moderately successful method is to pump the ruby more rapidly. The highest peak powers achieved have been obtained by inserting a Kerr cell light shutter between the end reflectors of the laser oscillator. The shutter prevents reflection to inhibit oscillation while the laser is pumped. When the cell is rapidly switched to a reflective condition, the laser breaks into an oscillation which uses up the stored energy in a fast intense burst. The resultant pulse yields megawatt power for times of the order of 10^{-8} seconds. A rapidly rotating mirror has also been used to vary the reflectivity.

The red ruby (0.5% Cr^{+++} in Al_2O_3) laser is a four-level laser. The lower levels involved in the oscillation are of the order of 100 cm^{-1} above the ground state so that effective four-level operation is only obtained at

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low temperatures. The hoped for low pump energy thresholds in four-level lasers has not been realized in red ruby.

Sm^{++} in CaF_2 is also a four-level laser. So far it has only operated at temperatures below 40^oK. Although it has a pumping threshold considerably below that of ruby, it has not proved to have any other operating characteristics as useful as those of the ruby laser. Further developments in crystal quality and pumping source developments are expected to improve the performance of this type of laser. The output pulse from the Sm^{++} laser is a continuous pulse without the spiked structure characteristic of the ruby laser.

U^{+++} in CaF_2 is also a four-level laser. It has been operated at temperatures up to about 0^oC. The lower level involved in the laser transition is about 500 cm^{-1} above the ground state. A number of wavelengths can be obtained, which depend upon the U^{+++} concentration and method of crystal growth. CW operation has not yet been attained, but may be possible. U^{+++} can be pumped either with green light or in the infrared in either the 8000-9500A. region or in the 12000-13000A. region. The amount of pump energy required is a strong function of temperature. Oscillation has been obtained with 40 joules into the xenon pumping lamp at 77^oK.

The U^{+++} in BaF_2 laser is similar to the preceding one. It has been made to oscillate at room temperature.

The He-Ne gaseous laser has characteristics considerably different from any of the solid lasers. It is CW in operation. Power is supplied from an rf oscillator to an electrodeless discharge in a quartz discharge tube. In presently operating lasers maximum power out is of the order of 15 milliwatts when operated continuously with higher peak powers when operated pulsed. Greater powers are possible by different design, but it is not possible to simply scale up the device by building a larger tube because the conditions of the discharge change with size. The frequency of the output has been stabilized to a frequency drift of about one part in 10^{10} per second. The difference in frequency of two different modes of the oscillator that are 300 megacycles per second apart has been held stable to a drift of about one cycle per second[2]. The beam divergence is approximately as small as can be obtained from a plane wave with the cross section of the laser. Considerable improvement in power output and stability is to be expected from He-Ne lasers.

The Nd^{+++} in $CaWO_4$ laser is a four-level, optically-pumped laser. The lower level of the laser transition is about 2000 cm^{-1} above the ground state so that four-level operation can be attained considerably above room temperature. The threshold for oscillation increases somewhat at higher temperatures due to line broadening. When pumped with a xenon discharge tube 5 joules were required to achieve threshold at room temperature and only 3 joules at 77^oK. The crystals used have been .07% neodymium by weight. Recently, continuous operation has been obtained with approximately 10 milliwatts output.

The Nd^{+++} in glass laser uses an energy level scheme that is similar to the previous Nd^{+++} laser. This type of laser has been made in the form of rods and fibers. The glass is 2% to 6% by weight neodymium. The great density of neodymium ions and the ease with which the glass can be made, in any shape or size, should make this type of laser very important. It can be pumped in any one of three absorption bands in the red, green, or blue. Beam divergencies approaching the theoretical limit have been achieved from 1/4" dia. rods.

Pr^{+++} in $CaWO_4$ laser uses a four-level scheme with the lower state 377 cm^{-1} above the ground state. It is pumped into three narrow absorption bands near 5000A. It has only operated at low temperatures.

The remaining masers on the list are all similar in behavior, utilizing four levels at various wavelengths. An exception is the organic system which depends upon electron level transitions in the naphthalene spectrum but obtains some of its pumping excitation by transfer from the benzophenone molecule. This is also the shortest wavelength operation reported to date.

Current laser work can be divided up into the following four categories: (1) research aimed at securing maser action in new materials and energy level systems; (2) development of improved and specialized operating characteristics of masers using proven materials and energy level systems; (3) investigation of systems applications of optical masers; and (4) applications of optical masers to scientific experiments.

Most of the present and proposed effort is going into work of the first category. There are a large number of promising maser schemes that are being studied, some of which will undoubtedly be in operation shortly. Amplification of 3.2 micron radiation in optically-pumped cesium vapor has been observed, and both 3.2 and 7 micron oscillation seems feasible. Work on a gaseous discharge in which mercury is excited by collisions with metastable krypton is also being carried on. This system has prospects of operating at a number of different frequencies and being more efficient than the present He-Ne maser.

Several experiments using the output of ruby lasers have been performed. Frequency doubling of the output radiation has been achieved by focusing it down to a small spot and making use of the nonlinearity of the dielectric constant of quartz and several other materials at high electric field strengths. A similar experiment has been performed with two ruby lasers of different temperature and thus, different wavelength focused on the same spot. Light of the sum of the two frequencies is observed in the output.

Applications of the optical maser are just now being attempted. Successful operation of a rangefinder and an optical radar are two of the significant feasibility results.

II. APPLICATIONS AND LIMITATIONS

Here are summarized the possible applications of optical and infrared masers with the advantages and limitations of the proposed uses. The material is divided into four categories. The first two, communications and radar, follow from the obvious extension of present uses to the infrared and optical spectrum. The third category, weapons, adds a new dimension to the use of electromagnetic radiation, since the maser seems to offer more promise in this area than schemes utilizing microwave radiation. The fourth and last category is highly speculative since it includes suggested miscellaneous uses which depend strongly on invention and specialized laboratory or manufacturing operations. In the sense that these techniques add to our technological capabilities they are felt to be a significant area for consideration.

In the lists below, each item is followed by a brief mention of the advantages and limitations. In most of these cases, it should be emphasized that the absorption and scattering by clouds, haze or smoke is universally limiting throughout the infrared and optical spectrum.

A. Communications

Type	Advantages	Limitations
Ground-to-ground	Economy, security, anti-jam, high data rate.	Requires pipes or clear weather.
Air-to-ground, air-to-air, ground-to-air	Secure, anti-jam, high data rate.	Clear weather only, pointing difficult.
Satellite-to-ground/air	Long range, high data rate.	Clear weather only, pointing difficult.
Satellite-to-satellite	Long range, high data rate.	Pointing difficult.
Submarine-to-submarine (sub-to-surface)	Security, radio techniques difficult.	High attenuation, greater than 3 db/100 yds. in green.
Plasma penetration (re-entry, etc.)	Ionized media transparent when opaque to radio or microwave.	Pointing difficult.

B. Radar

Type	Advantages	Limitations
Rangefinders (mortar, artillery, etc.)	High resolution, precision, compactness.	Clear weather only.
Surveillance	High resolution, haze and cloud penetration by range discrimination.	Relatively clear weather only.
Ground-to-ground	Battlefield use, night vision, secure.	Non-visible wavelength.
Air-to-ground	3-D data, mapping.	Scan rate.
Underwater	Resolution, backscatter elimination by range-gating.	Attenuation.
Tracking	Resolution.	Clear weather only.
Ground-to-air/satellite	Resolution, daylight use by wavelength discrimination.	Clear weather only.
Air-to-air/satellite	Compactness, weight precision.	Acquisition.

C. Weapons

Sensor destruction (IR homers, optical and IR surveillance, human eyes)	High resolution and available power offer efficient instantaneous kill.	Wavelength should probably match that of sensor. Pointing difficult.
Low-level damage (puncture, etc.)	Instantaneous, secure, covert action.	Pointing problem.
High-level damage	Anti-vehicle, anti-personnel, anti-missile.	Refractive effects, extremely high power required.

D. Miscellaneous

Type	Advantages	Limitations
Instrumentation (spectroscopy, etc.)	Intense monochromatic source.	
Fabrication techniques (welding, etching, cutting, etc.)	Precision, speed, high resolution.	
Weapon simulation (X-ray blow-off, etc.)	High power densities.	
Power transmission	Narrow beam.	
Microphotography	Photographic speed.	
Photochemistry	Higher reaction rates.	

III. RECOMMENDED AREAS OF RESEARCH

In order to realize even a small fraction of the above suggested applications, it will be necessary to carry out a strong program in fundamental maser research as well as in auxiliary techniques. At the present time, the most serious shortcoming is the availability of continuous sources at reasonable power level as well as pulsed high power sources with a high-duty cycle. The development of such devices should lead to immediate implementation of many of the applications suggested, at least on a feasibility basis. Concurrent with these developments are those required in auxiliary areas. These are also included in the listing below.

A. Fundamental Device Studies

1. Solid, gaseous, and liquid (?) masers: CW operation, extension of operation to shorter and longer wavelengths, alternate pumping schemes, higher power.

2. Pump sources: gas discharge (rf and dc), incandescent, electrical (such as carrier injection), flames, nuclear reactors, dynamic pinch.

3. Mixers, multipliers, and modulators: studies of non-linear effects, photoemission.

4. Optical resonators, filters, waveguides, etc.: precision and stability under high power.

B. Auxiliary Studies

1. Susceptibility of materials to radiation.

2. Attenuation, transmission, breakdown and ionization at high electric fields (at optical and infrared frequencies).

3. Crystal production techniques.

IV. STATUS

The applications of Section II and the research areas of Section III are felt to be reasonably well covered at the present moment. As more scientific personnel and laboratories acquire competence in the field, the research program should logically expand. Similarly, extra funding will be needed on a more specific basis as applications requirements are more firmly established.

Appendix I lists all contracts in force arranged according to contractor and separated somewhat arbitrarily into research and applications. It should be emphasized that, especially in the research area, a large amount of work is being carried on under private support or under Joint Services contracts with university laboratories and thus is not completely covered in the appendix. In such a rapidly expanding field, the committee felt that it would be impossible to catalogue this type of work, both because of the rate of growth and the proprietary nature of many new experiments. Areas which should be expanded or reduced in terms of support have not been delineated by the committee since it is felt that this task should be carried out through the coordination process to be discussed in Section V.

The committee briefly surveyed the state-of-the-art in the foreign area and concluded that, at least in the case of the European countries, both the amount and status of such work is lagging appreciably behind our own program. There are, of course, special areas where individual groups in the research area are making gruitful contributions and these should be monitored. In general, liaison with these activities is well covered through such efforts as the ONRL European Scientific Notes and the MWDP program, as well as the frequency exchange of visits under these and other programs.

The situation in the Soviet Union is not as clear, since their applied electronics program is so closely guarded. No intelligence information was obtained which would indicate any unusual new developments; however, this technical area deserves continuous attention. The Russians have been quite strong both in the theoretical aspects of masers and also in the materials area where their fundamental spectroscopic work has yielded several new materials used fruitfully in the U.S. program.

V. RECOMMENDATIONS FOR COORDINATION

The optical and infrared maser program embraces scientific areas in such diverse fields as optics, electronics, chemistry and weaponry. In addition, it is felt that significant applications will be achievable within a short time period. On this basis, it is felt that coordination of this effort should be carried out in the Office of Electronics of the Director of Defense Research and Engineering.

Specifically, the committee recommends:

1. That a technical coordinator or secretary for optical and infrared maser activity be appointed and that he be directly and solely responsible to the Director of Electronics.

2. That a coordination committee be designated which shall consist of one representative from the Army, Navy, Air Force, ARPA, and NASA.

3. The representative of each of these organizations shall have full knowledge and/or cognizance of all optical and infrared maser activity within his own service or agency, including R&D contract support as well as all existing or contemplated uses in systems programs.

4. The technical coordinator or secretary shall maintain a list of all contracts in force with a brief description thereof and shall also maintain a library of all progress reports under the various contracts.

5. The committee shall meet with the coordinator at least once a year to review present and planned programs and funding. Extra meetings shall be held when significant technical advancements or contract developments so warrant.

6. Upon issuance of a contract by one of the services, a brief description of the work shall be forwarded to the coordinator, as well as all members of the committee. In addition, these individuals shall be placed on the distribution list for all progress reports under the contract.

7. The coordinator shall maintain a list of scientific consultants in the field, who may be called upon by himself or the individual service representatives for review of proposals and who may also be requested to attend and advise the committee while in session.

CONCLUSION

The committee feels that the information in Sections II and III, as well as the present contract status in the Appendix, is an adequate working source for the successful coordination of optical and infrared maser activity by the coordinating group proposed above. We have not recommended specific funding or increases or decreases in specific areas, since the field is moving so rapidly that any such recommendations would become rapidly obsolete. It is more essential that the areas outlined in this report be adequately covered by competent research and development groups and that new research or application possibilities be considered as they develop.

In conclusion, the committee recommends that, subject to DDRE approval of the above proposals, the coordinating group meet at the earliest possible date to review their present and future plans in the light of the present report.

Respectfully submitted,

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J. V. Burke, AFSC, Air Force Representative
R. C. Weidler, ARPA
J. R. Sinclair, NASA
I. Rowe, ONR (Representing Quantum Electronics Conference)
H. J. Sullivan, A.G.E.D., Secretary

APPENDIX

The following is a list of all present contracts in force, but does not include fundamental studies carried out under Joint Services Contracts, in-house work, or privately sponsored work. The listing is not complete, but is representative. It is estimated that there is possibly 20% more funding in force than indicated. In addition, contracts contemplated or under discussion would add an additional sizeable amount.

APPLICATIONS

Contractor	Title	Service	Annual Funding
Dayton University	University of Dayton Reflection, Background S/N Detection Study.	AF	95K
Electro-Optical Systems, Inc.	Feasibility Study of a Laser Beacon for Daylight Tracking and Navigation.	NASA	25K
Hughes Aircraft Co., Culver City, Calif.	High PRF Laser Transmitting for Surveillance.	AF	65K
Hughes Aircraft Co., Res. Labs (Malibu)	Surveillance Radar Study.	AF	62K
Hughes	Feasibility Study of Range Finders.	A	37.9K ~~379K~~
Philco Res. Div.	Space Laser Communication Links.	AF	100K
RCA (Camden)	Correlation Techniques (Confidential Project)	AF	95K
Technical Res. Group	Feasibility Study of Range Finders.	A	35K
	Applications Total		~~856K~~ 514.9K

RESEARCH

Contractor	Title	Service	Annual Funding
Alpens (Paris, France - P. Aigrain)	Semiconductor Maser.	N	20K
American Optical Co.	Sun Powered Laser.	AF	98K
Bell Telephone Labs.	Optical Maser Research.	A	99K
California University (Berkeley)	Pulse Inversion of Electric Dipole Moments and Modulated Coherent Optical Emission.	A	47K
Columbia Radiation Lab.	Study of Infrared and Optical Masers.	A	
Corning Glass Works, Bradford, Pa.	Optical Delay Line.	AF	79K
Electro-Optical Systems, Inc.	Laser Amplifier.	AF	100K
Electro-Optical Systems, Inc.	Pump Sources.	AF	90K
Hughes Res. Lab.	Coherent Generation of Optical Radiation.	AF	370K
Hughes	Double Pumping Study (Feasibility).	ARPA	300K
Isomet Corp.	Large Crystals.	AF	84K
ITT Labs.	Infrared Laser and Harmonic Generation.	N	45K
Maryland University	Microwave Maser (Includes Optical Pumping and IR Maser)	N	18K
Michigan Project	Materials, Range Finders, and CW Laser.	A	

Research (Cont'd)

Contractor	Title	Service	Annual Funding
MIT (RLE)	Electron Resonance Research.	A	50K
Motorola	Pump Sources (High Intensity)	AF	52K
Oak Ridge Nat. Lab.	Gas Laser.	ARPA	240K
Optics Technology, Inc.	Fiber Optics Scanning Techniques (Conf. Project).	AF	87K
Quantatron	Infrared Maser Objective - Dev. of Infrared Ranging System.	N	90K
RCA	Very Narrow Band Sources, Modulators and Detectors.	AF	400K
Rochester Univ.	Investigations of Optical Masers.	A	60K
Sperry Gyroscope	500-1000 Mc Modulator (Confidential Project).	AF	100K
Stanford University	Maser Research.	A	40K
Technical Research Group, Inc.	Modulation Methods.	AF	50K
Technical Research Group, Inc.	Theoretical Study of Laser Oscillations.	AF	25K
Technical Research Group, Inc.	Laser Research.	ARPA	500K
	Research Total		3,044K
	Grand Total		~~3,900K~~ 3,558.9 K

bf: 3/12/62